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The Development of a Family of Resistojet Thruster Propulsion Systems for Small Spacecraft

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Abstract

The advance in complexity and sophistication of small satellite missions is increasingly requiring that these spacecraft have on-board propulsion systems. However, there is a different emphasis on these small systems as opposed to the traditional propulsion systems on larger spacecraft. The systems must be low cost, low volume and safe.

Traditionally cold gas nitrogen systems have been used as they provide a simple solution, combining high reliability with low cost and heritage. However cold gas systems tend to be limited by fairly low specific impulses and poor storage densities. One method of enhancing their performance, hence extending the mission life, is by heating the propellant to achieve a higher exhaust velocity. When this is done electrically with resistance heaters it is known as a resistojet. One feature of small satellites is that they are often power limited. Hence a balance must be struck between the propulsion system power requirements and the rest of the spacecraft. This paper will describe some of the features and limitations of using resistojets on small spacecraft and the evolution of the Surrey family of thrusters.

Introduction

Traditionally small spacecraft have used either cold gas nitrogen propulsion systems or hydrazine monopropellant systems. The move from nitrogen to hydrazine gives a step change in the system performance, however it also gives a step change in the cost. SSTL's current generation of spacecraft typically require a delta V capability somewhere between that of nitrogen and hydrazine, however a hydrazine system is cost prohibitive.

Resistojet thrusters are an ideal way of improving the performance of a cold gas system without incurring the increased cost of safety associated with hydrazine. They allow improvement in two ways. Firstly the heating of the propellant increases the exhaust velocity of the propellant, hence more impulse is transferred to the spacecraft per unit mass of propellant. Secondly the resistojet can act as a vaporiser, which allows the use of liquefied gases as propellants. As these store at a higher density than compressed gases they give a higher density specific impulse, hence more impulse per unit volume of propulsion system.

Background

The use of resistojet thrusters improve the performance of the propellant by heating the working fluid before it enters the thruster's expansion nozzle. From classic thermodynamics the sonic velocity of the propellant at the throat of the thruster is given by: -

$$V_{throat} = \sqrt{\gamma R T_{throat}}$$

Where
γ = Ratio of specific heats of the exhaust gas
R = Gas constant for specific gas

Hence the propellant velocity at the throat is proportional to the square root of the absolute temperature. The higher the throat velocity, the higher the nozzle exit velocity, and hence the higher the performance in terms of specific impulse.

As a result even modest increases in propellant temperature can give significant performance increases. An increase in propellant temperature from ambient to just over 300°C (300K to 600K) will give a specific impulse increase of around 41%, assuming insignificant changes of γ with temperature. If the temperature can be increased to around 900°C the specific impulse can be almost doubled.

Hence if the power can be found to heat the propellant, then significant performance increases can be achieved over cold gas mode.

Thruster and System Design Requirements

There are a number of basic practices followed by SSTL, which minimise the cost of adding resistojet thrusters onto a basic cold gas system.

SSTL uses the "80 / 20 rule" when designing resistojet thrusters. This states you can get 80% of the ideal performance, for only 20% of the cost of a traditional thruster. This is discussed fully in reference 1, however by not optimising the thruster design to achieve the last few seconds of Isp the costs of the thruster can be kept low.

Commercial Off The Shelf Technology is also used, as discussed in reference 2.

Most of the thrusters designed at SSTL use a remote valve configuration. This means that the thruster / heater assembly is designed independently of the Flow Control Valve (FCV). The following advantages are obtained using this philosophy: -
- The FCV can be changed for technical or commercial reasons without affecting the qualification status of the thruster.
- The FCV can be located inside of the spacecraft in a more thermally benign environment.
- The FCV is thermally isolated from the high temperatures of the thruster chamber assembly.

As most cold gas systems have their thruster nozzle integral in the outlet of the FCV the only modification required when adding a resistojet is to change the outlet fitting of the FCV and directly connect the thruster inlet to it.

The thruster heater element is designed to operate from the 28 Vdc bus on the spacecraft. As a result the only electronics required is the On / Off switch for the heater. This is opposed to some high power resistojets, which require additional expensive electronic power processing units.

The resistojet system must be designed around the available power. Typically the spacecraft power budget will be split into the payload power and platform power. In virtually all of SSTL's applications the payload will be switched on only for certain orbits. For example, earth observation missions will typically not be operating during orbits that cover the oceans. Consequently there will often be a number of orbits per day in which the payload power level will be available. If these orbits tie in with the propulsion requirements, then a "payload or propulsion" strategy can be adopted. The resistojet heaters can be sized to make full use of the available power, when the payload is not operational.

High power resistojet

The first flight resistojet thruster developed at Surrey Space Centre was a 100 Watt resistojet, which was flown on the UoSAT-12 spacecraft in 1999. That programme is fully described in reference 3. UoSAT-12 is a 325 kg spacecraft, which generates in the order of 60 Watts orbit average power. Hence the 100 Watt power requirement of the thruster was acceptable for reasonably short durations, whilst the payloads were switched off.

Figure 1 shows a section view of the thruster. The cartridge heater is powered directly from the 28V spacecraft bus. This raises the thruster operating temperature to around 800ºC. A bed of silicon carbide granules surrounds the heater. The propellant passes through this bed and heats up.
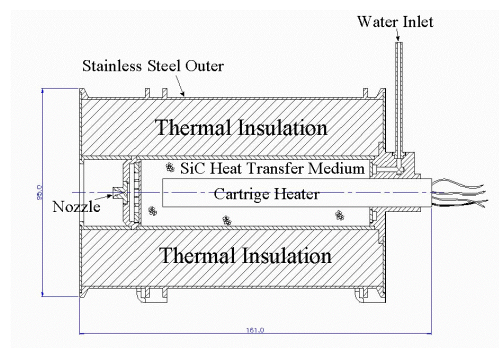

Figure 1 – 100 Watt resistojet

The thruster was flown on UoSAT-12 with nitrous oxide as the propellant and has also been qualified for use with water. It has also

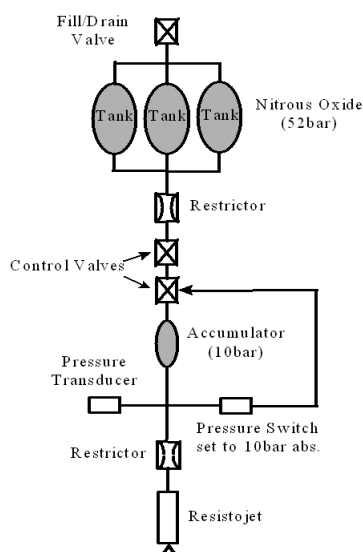been successfully operated with nitrogen, helium and ammonia.

Figure 2 – UoSAT-12 nitrous oxide system

Figure 2 shows the propellant feed system schematic for UoSAT-12. It is a conventional bang-bang regulation system using pressure feedback and is clearly no more complicated than traditional cold gas nitrogen feed systems. The advantage of using a resistojet with nitrous oxide over a conventional cold gas propulsion system can be seen by examining the UoSAT-12 spacecraft budgets.

The resistojet system uses 2.1 kg of nitrous oxide to give up to 9.7 m/sec delta V on the spacecraft. There is also a cold gas nitrogen system on UoSAT-12. This uses 6.4kg of N_2 to give the spacecraft 14 m/sec delta V. Hence the nitrous oxide resistojet system has around a third of the propellant mass, but gives two thirds the performance. The nitrous oxide system also has a much lower dry mass and lower volume.

Figure 3 shows the UoSAT-12 propulsion panel with both the nitrogen and nitrous oxide systems fitted. The nitrous system is contained within the aluminium box on the left with the three cylindrical tanks. The nitrogen system is contained within the aluminium box on the bottom right and three spherical tanks (with the red protective covers). It is clear that the resistojet system occupies a significantly less volume.
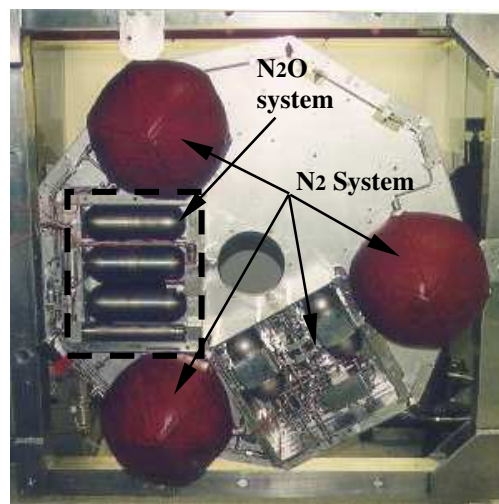

Figure 3 – UoSAT-12 propulsion panel

The resistojet has been successfully used in orbit and the benefits of its use are clear. However the thruster is sized incorrectly from the point of view of power and mass for SSTL's current range of enhanced micro-satellites, which weigh 80 – 150 kg and have orbit average powers of around 40 Watts. A power budget review showed that only 15 Watts of power would be available.

<u>Low power resistojet</u>

A smaller, lower power resistojet thruster was designed and first flown on ALSAT-1 spacecraft in Nov 2002. Its design and qualification are described in detail in reference 4. The thruster mass was reduced from 1,200 grams to 60 grams and the power consumption from a single 100 Watt heater to prime and redundant 15 Watt heaters. Major mass and volume savings were made by reducing the substantial thermal insulation on the 100 Watt unit to a simple heat shield on the 15 Watt unit. This approach has a number of advantages and disadvantages. It reduces the maximum operating temperature from 800°C to around 500°C, hence the increase in Isp is not as marked. It also reduces the mass flow rate, hence thrust. However the warm up time is quicker with the smaller unit.

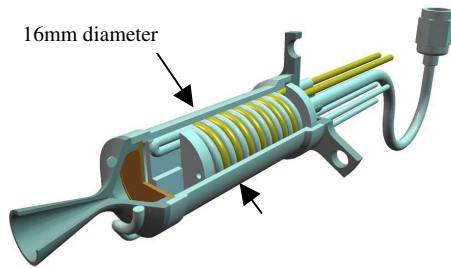The thruster design is shown in sectioned view in figure 4.

Figure 4 – Sectioned view of the thruster

The thruster has a standard convergent / divergent nozzle with a throat diameter of 0.42mm. This is approaching the lower limit of what can be machined with a regular machine shop capability. Any smaller requires costly machining techniques. The throat is protected with a 10 micron filter disc immediately upstream. Consequently no special cleanliness precautions are required when winding the heaters on the bobbin.

The thruster is made of conventional materials, with all the machined parts being stainless steel. The heaters and propellant feed tube are brazed into the chamber and the case is welded closed.

For all the current applications the thruster is fitted in a remote valve configuration. The flow control valves being located on the main propulsion panel, inside the spacecraft. The thruster has no thermal insulation, however it has a simple aluminium heat shield around the chamber as can be seen on the first flight unit shown in figure 5.
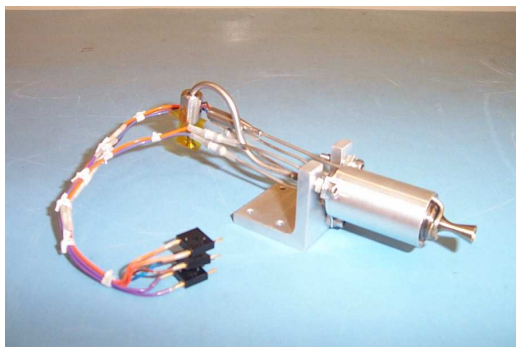

Figure 5 – the ALSAT-1 flight thruster

The propulsion system for the DMC spacecraft is shown schematically in figure 6. It can be seen that the butane propellant is stored in two propellant tanks. The outlet of one of these tanks is connected to series solenoid valves, which isolate the single resistojet thruster. The system is operated by opening the FCVs and

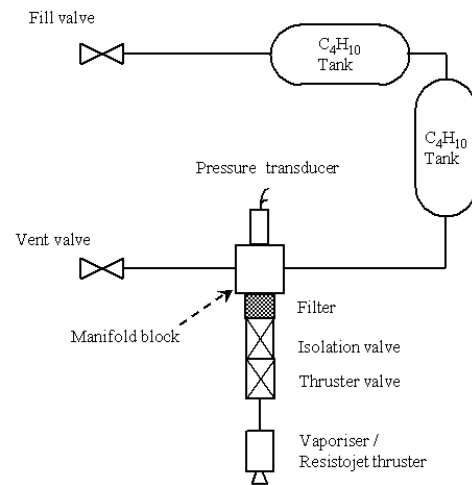allowing the propellant to flow under its own vapour pressure, approx 2 bar absolute.

Figure 6 – DMC propulsion system schematic

The propulsion system can be seen fitted to the UK-DMC spacecraft in figure 7. This spacecraft is a conventional SSTL microsatellite core module stack fitted with larger honeycomb panels top and bottom to allow for additional equipments and to increase the external area available for solar cell population. Although this is a good packaging concept for the rest of the spacecraft, it is certainly not the optimum for the propulsion system. The only volume available for the propulsion is between the central stack and the solar panels. This drives the design to using cylindrical propellant tanks, as spherical tanks of any reasonable size would not fit. Two propellant tanks are seen on the lower, space facing, panel.

The propellant used in this system is butane. It stores in the liquid phase, at density greater than twice that of nitrogen compressed to 200 bar. Hence to get the same overall performance from a nitrogen system an extra two propellant tanks would be required in the same area of the spacecraft. The propellant tanks would then have to be mounted one above the other, or vertically, to fit in the same volume. The fact that butane can be used is primarily down to the resistojet thruster, which in this case also acts as a vaporiser to ensure that none of the liquid phase propellant can be expelled.

Figure 7 – UK-DMC spacecraft in launch preparation

ALSAT-1 In flight performance

The first resistojet system of this type was flown on ALSAT-1 spacecraft. It was launched on 28th November 2002 on a Cosmos launch vehicle from Plesetsk Cosmodrome in Russia.

It was targeted for a circular 680km orbit. However launch injection errors were outside the 3 sigma levels and the final orbit ended up with an apogee of around 745 km. Due to the fact that 3 further DMC spacecraft are to be launched in July 2003 to form a complete constellation, the orbit had to be recovered to be very close to its intended level.

Following a series of propulsion checkout firings, the orbit correction manoeuvre series began on 26th March 2003 and lasted through to 30th April. An average of 5 x 3 minute firings were performed per day, giving a total of 168 firings. The orbit apogee was reduced from 745.5 km to 693.61 km, which is equivalent to a total delta V of 14.5 m/sec. This is sufficient to keep the LTAN (Local Time of Ascending Node) at greater than 10:00am throughout the mission life, and hence meet the mission specification, despite the large initial injection error. This will allow the imaging to be performed with constant shadow length, for easy comparison, over the mission.

Figures 8 & 9 show the details of the orbital parameters and how they changed during the sequence. Further manoeuvres may be required once the next 3 spacecraft are launched, depending on their final injection orbit.
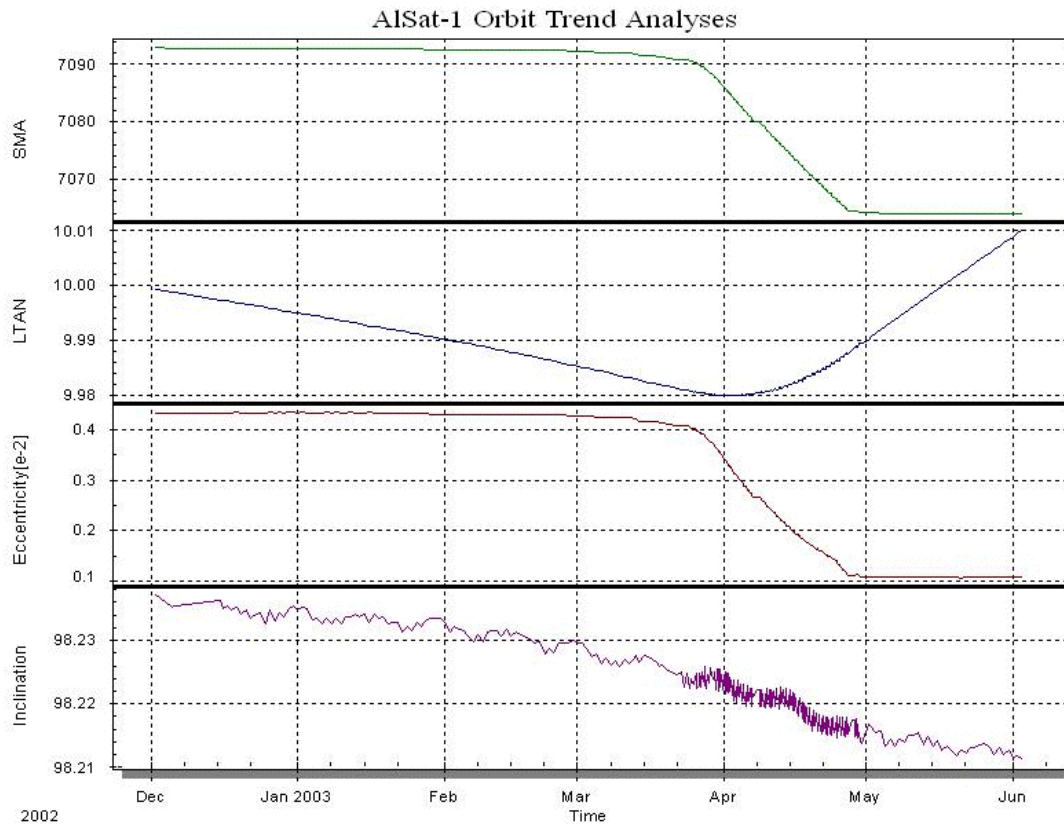
Figure 8 – ALSAT-1 orbital parameters over the first 6 months in orbit
SMA - semi major axis in km
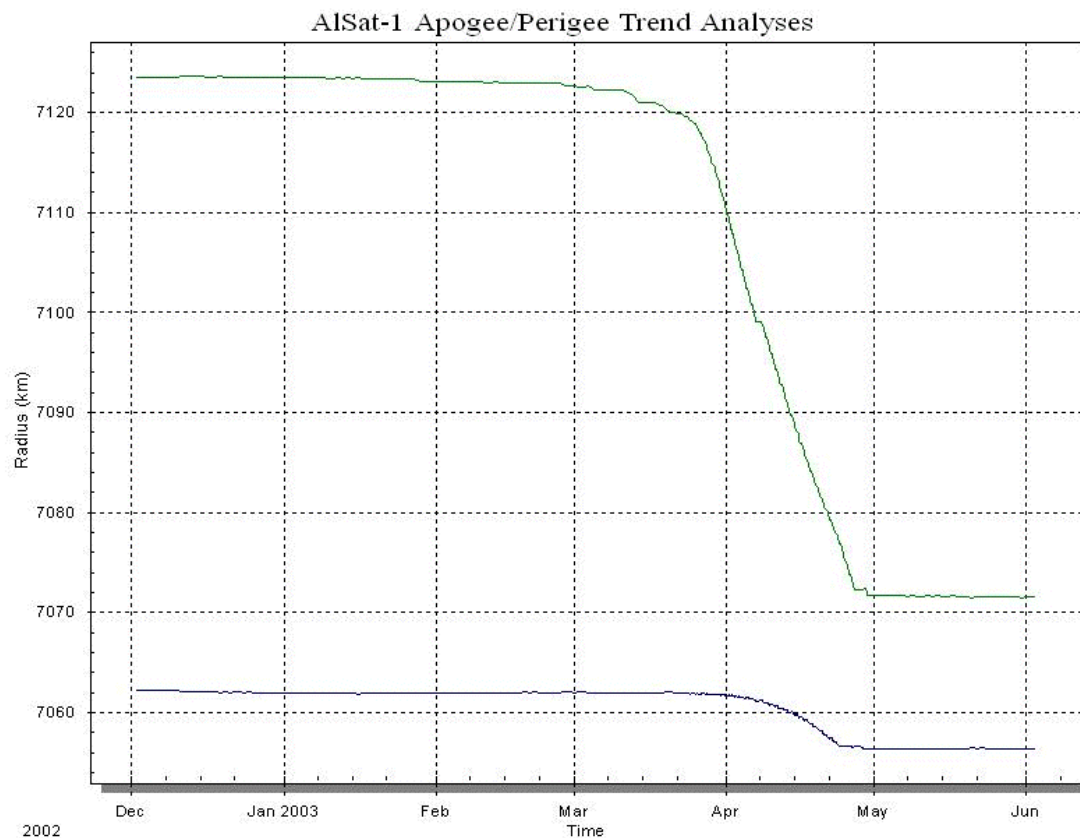*LTAN – Local Time of ascending Node*

Figure 9 - ALSAT-1 orbital parameters over the first 6 months in orbit

During the series of 3 minute firings the imager was used sparingly, hence the power saved by not having the payload on was used for propulsion. Both thruster heaters were used simultaneously for the warm-up and firing. The thruster warm up was performed for 6 minutes (at 30 Watts total power) allowing the indicated temperature to rise to over 300°C. Once the propellant flow began, the thruster would start to cool down. By the end of the firing the chamber temperature was typically 200°C. Models of the thruster operation predict average specific impulses of 100 seconds during these firings. However the specific impulse figure cannot be fully confirmed, as it is difficult to accurately gauge the amount of butane consumed. The mass flow rate is calculated using parameters measured during ground test.

This model of resistojet thruster has become the standard baseline for all current SSTL missions requiring propulsion systems. It will be launched on NiSat-1, UK-DMC and BilSat-1 in July 2003, and China DMC+4 in 2004. Additionally it has been baselined for the GSTB-V2 and PROBA 2 missions.

Micro-resistojet

SSTL's low power resistojet has its niche in the microsatellite range, however SSTL are also investigating missions on nanosatellite platforms (<10 kg spacecraft mass), where propulsion is a requirement. SSTL's first nanosatellite mission SNAP-1, launched in June 2000, had an orbit average power of around 6 Watts. Hence with these low power levels it is clear that even the existing thruster with 15 Watt heaters, weighing 60 grams is too large. Further reducing the size of the spacecraft to Surrey's Palmsat concept (~ 1kg) makes lowering the power and mass more critical.

On such small spacecraft the propulsion system mass and volume become even more critical. Studies show that the optimum propellant stores at high density and low pressure, hence propellants storing, as liquids are a very good option. Butane and water are both suitable candidates. The main disadvantage with these propellants is that they must be exhausted in the vapour phase. If liquid propellant is exhausted the system specific impulse decreases dramatically. Hence the primary function of a resistojet thruster on such a small water or butane system is to act as a vaporiser.

The propulsion system on SNAP-1 weighed 450 grams, including 32.6 grams of butane propellant. The thruster was a conventional cold gas thruster, without any additional heat input. Using the theoretical Isp, the spacecraft should have achieved 3.4 m/sec delta V. Figure 10 shows the variation of semi major axis of the SNAP-1 spacecraft and Tsinghua-1, the other SSTL spacecraft on the same launch. It can be seen that SNAP-1 was released into a lower orbit than Tsinghua-1 and immediately they started drifting apart. By the time the propulsion system on SNAP-1 had been commissioned they had drifted by 15,000 km in track. The SNAP-1 propulsion system raised the spacecraft's semi major axis by around 4 km to cause the two spacecraft to drift together again. They returned to within 2,000 km before starting to drift apart again, not quite close enough to use the inter-satellite link between the two spacecraft.
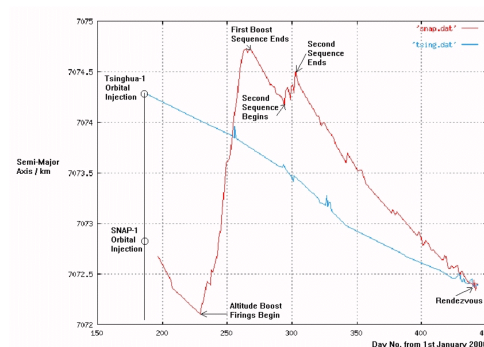

Figure 10 – Semi major axis history for the SNAP-1 spacecraft (red trace)

The total delta V achieved by the spacecraft was 2.1 m/sec. Whilst this is a significant achievement on such a small spacecraft the full potential of 3.4 m/sec was not achieved. Analysis of the flight data [ref 5] showed that during the early firings liquid phase propellant must have been exhausted, hence the system suffered a significant reduction in performance. If a small resistojet with a few Watts of power had been available for this mission, then that propellant could have been used more efficiently and the in-track distance reduced by enough to bring the spacecraft back within the 100 km required to operate the inter-satellite link.

As a result of this experience, SSTL have developed a smaller resistojet thruster. This weighs around 15 grams and operates on 3 Watts of power. A flight opportunity arose on

the UK-DMC, to be launched July 2003, and hence a small micropropulsion experimental system was constructed to fly on this spacecraft.

The flight thruster is shown in figure 11. It was designed to be easily manufacturable in SSTL's limited workshop facilities. It uses a spiral thread form internally as the fluid flow passage. The heating element is wound externally on the chamber. The element comprises of high resistance Ni-Cr thermocouple wire, with PTFE insulation sleeving. The insulation limits the temperature to around 250°C, however the heater rating of 3 Watts was chosen such that the thruster equilibrium temperature in vacuum is around 200°C.

Figure 11 – UK-DMC's micro-resistojet

The experiment was loaded with 2.06 grams of de-ionised water propellant. This was performed in the clean room at SSTL taking about 30 minutes on the spacecraft. The system was then shipped to the launch site with propellant already loaded.

The in-orbit operation plan is to use the thrust generated (around 0.5 mN) to apply a torque around the Z axis of the spacecraft. This torque would then be reacted on the Z axis reaction wheel to give measurements of the thrust.

The water propulsion system is shown in figure 12 mounted on the existing butane propulsion system on the UK-DMC spacecraft.
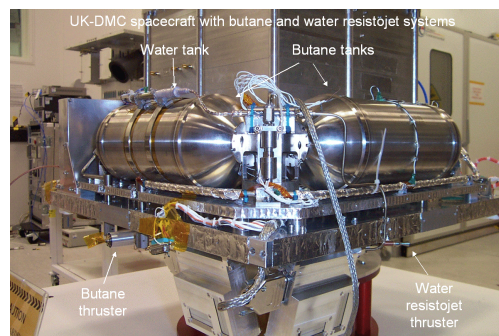

Figure 12 – Water micropropulsion experiment on UK-DMC

Future developments

Given the advantages of resistojet thrusters identified above, SSTL is investigating new generations of thruster, which will give higher performance, whilst still retaining the "Affordable Access to Space" ethos of SSTL. A programme has begun to investigate the use of carbon micro-tubes as both the heating element and heat transfer matrix. Testing is in early phases so no results are available as yet.

Conclusions

The use of resistojet thrusters can significantly enhance the performance of propulsion systems on small spacecraft. With careful planning the resistojet thruster can be operated whilst the payload is not, hence the spare power can be used for propulsion purposes.

The use of the resistojet provides the following benefits: -

- It enables higher thruster performance in terms of propellant Isp, which can mean higher delta V for a given system volume or reduced system volume and mass for a given deltaV
- In a vaporiser mode it enables the use of liquefied gases, such as butane and water, which further reduces the volume requirement and storage pressure of the propulsion system, making the propellant tanks smaller and lighter.

SSTL has successfully used resistojet thrusters on two of its missions. UoSAT-12 used a 100 Watt thruster with a nitrous oxide system. ALSAT-1 used a 15 watt thruster with a butane feed system. The ALSAT-1 system was used to perform a major orbit changing manoeuvre, by lowering the apogee by 52 km through a series of 168 firings.

Further information on SSTL can be found at web site **www.sstl.co.uk**.

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